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• **Original Paper** •

Modeling Aerosol Climate Effects over Monsoon Asia: A Collaborative Research Program

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ABSTRACT

This paper describes the latest progress of a collaborative research program entitled "Modeling Aerosol Climate Effects over Monsoon Asia", under the Climate Sciences agreement between the U.S. Department of Energy and the Chinese Academy of Sciences (in the early 1980s, Professor Duzheng YE played a critical role in leading and formalizing the agreement). Here, the rationale and approach for pursuing the program, the participants, and research activities of recent years are first described, and then the highlights of the program's key findings and relevant scientific issues, as well as follow-up studies, are presented and discussed.

Key words: aerosol–cloud–climate interactions, monsoon Asia, climate models

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1. Introduction

The Climate Sciences agreement between the U.S. Department of Energy and the Chinese Academy of Sciences, which was initiated in early 1980s jointly by Duzheng YE and Fredrick M. KOOMANOFF and signed on 13 August 1987 (Koomanoff et al., 1988; Riches et al., 1992; Tao et al., 1999), originally concentrated on the "greenhouse effect". But, over the years, the agreement has expanded to include, in addition to global warming, more imminent climate and environmental issues, with current collaborative studies focusing on aerosol climate effects—in particular, climate modeling studies.

1.1. *Aerosol climate effects*

1.1.1. *Direct radiative effects*

Fossil fuel and biomass burning due to human activities increases the tropospheric concentrations of black carbon and primary organic aerosols, and chemically active precursors of sulfate, nitrate and secondary organic aerosols (Isaksen et al., 2009; Wang et al., 2012). Increases in black carbon aerosols warm the atmosphere by increasing the absorption of solar radiation, and the surface by decreasing the snow albedo; while increases in atmospheric sulfate, nitrate and organic aerosols cause a direct cooling effect by scattering solar radiation and thus increasing the Earth's albedo. Observational studies have linked the atmospheric aerosol loading to the amount of solar radiation reaching the surface (e.g., Wild, 2009) and to the clear-sky visibility (e.g., Wang et al., 2009).

1.1.2. *Aerosol–cloud interactions*

More importantly, however, aerosols can act as cloud condensation nuclei to regulate the cloud droplet number and size, thereby changing the cloud albedo, cloud lifetime, and precipitation. Thus, aerosol climate effects concern intricate aerosol–cloud–radiation–precipitation interactions.

For example, most aerosol–cloud interaction studies involving warm clouds indicate consistent responses in cloud properties: more aerosols result in more but smaller cloud droplets and thus larger cloud albedo; the smaller cloud droplets reduce the efficiency of cloud droplet coagulation and raindrop formation and thus usually prolong the cloud lifetime. Moreover, the reduced raindrop formation will lead to less or less-intense precipitation. Suzuki et al. (2013) used satellite observations to provide evidence of rain suppression due to increased aerosols. They further employed models to illustrate how the formation process of warm rain is modulated by different aerosol conditions and demonstrated that the models have fundamental bias in terms of the process, which in turn biases the influences of aerosols on precipitation.

The effects of aerosols on precipitation for mixed-phase and ice clouds are highly uncertain. A comprehensive review of current understanding of the interaction was given by Tao et al. (2012), in which the fundamental theories, observations and numerical modeling studies were presented. They summarized that "Basically, aerosol concentrations can influence

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cloud droplet size distributions, the warm-rain process, the cold-rain process, cloud top heights, the depth of the mixed-phase region, and the occurrence of lightning." They further highlighted the need to meet the challenges of identifying and attributing the aerosol effects on precipitation using a combination of observational analyses and general circulation model (GCM) simulations. However, at present, because of their complexity and our inadequate understanding of them, aerosol–cloud–radiation–precipitation–climate interactions are recognized as one of the most uncertain aspects of using GCMs to project future regional climate changes.

1.2. *Aerosols over East Asia*

The climate effects of aerosols are significant over the land regions of the Northern Hemisphere—in particular, those of sulfate aerosols over monsoon Asia, North America and Western Europe, where significant anthropogenic SO_2 emissions have been observed (Isaksen et al., 2009; Wang et al., 2012) and concentrations of other aerosol species are also high (Zhang et al., 2012). However, monsoon Asia is different from the other two regions in at least three aspects.

First, while SO_2 emissions in North America and Western Europe have decreased since the mid-1980s due to stricter regulations, the trend of emissions increasing over monsoon Asia has continued, especially over South Asia, causing serious environmental problems locally, and at the same time imposing adverse environmental implications upon other parts of the Northern Hemisphere. Second, the climate over monsoon Asia, especially over eastern China, is distinct in terms of its summer and winter monsoons. This can result in different production (such as clean-air and in-cloud oxidation of SO_2) and removal (such as wet scavenging) processes that affect the chemical lifetime (Tsai et al., 2010) and thus the atmospheric loading of aerosols (Zhang et al., 2010; Zhu et al., 2012). Meanwhile, monsoon circulations control the water vapor that affects aerosol optical properties (Li et al., 2012, 2014) and cloud formation (Li et al., 2017). And third, the vertical cloud structure varies significantly with the progression of the seasons (Li et al., 2004; Wang et al., 2004), which may induce different aerosol–cloud microphysical interactions.

2. Collaborative research

We have been conducting modeling and observational studies of aerosol climate effects over monsoon Asia—in particular, over eastern China. Because of the multidisciplinary nature of the topic, involving aerosol emissions, atmospheric chemistry, aerosol optical properties, cloud microphysics, atmospheric radiation, and meteorology (see Fig. 1; Stevens and Feingold, 2009), we have taken a collaborative approach using two existing research platforms: the first, since 1994, with Guoxiong WU/Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences on "East Asia Climate (EAC)"; and the second, since 1997, with Jen-Ping CHEN/NTU on "East Asia Climate and Environment (EACE)". While the former aims at evaluating models' ability in simulating the climate features (e.g., summer monsoon) for further model improvement, the latter studies changes in atmospheric composition (e.g., ozone and aerosols) and climate–chemistry interactions over East Asia.

Because of the important roles played by aerosol emissions and atmospheric physics and chemistry in modeling global aerosols, these collaborations have been expanded in the last couple of years to include another three modeling groups (see Fig. 2): Huang-Hsiung HSU/Research Center for Environmental Changes (RCEC); Huiwen XUE/Peking University (PKU); and Hong LIAO/IAP (now at Nanjing

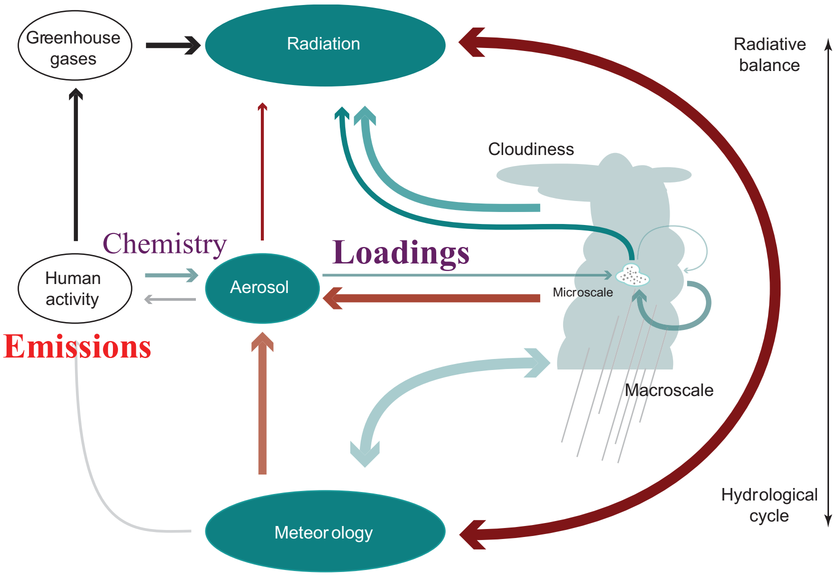


Fig. 1. Untangling the effects of aerosols on clouds and precipitation in a buffered system. Modified from Stevens and Feingold (2009).

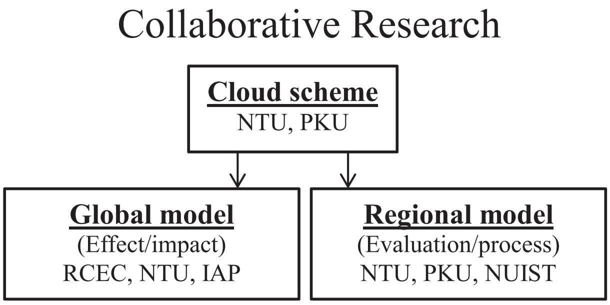


Fig. 2. Participants in the collaborative research program entitled "Modeling Aerosol Climate Effects over Monsoon Asia": RCEC, Research Center on Environmental Changes, Academia Sinica; NTU, Department of Atmospheric Sciences; IAP, Institute of Atmospheric Physics, Chinese Academy of Sciences; PKU, Department of Atmospheric and Oceanic Sciences; NUIST, Nanjing University of Information Sciences and Technology.

University of Information Sciences and Technology, NUIST). The collaborations have been very productive, resulting in many joint journal publications, most notably on aerosol radiative effects (Li et al., 2012, 2014, 2015), aerosol–cloud microphysical interactions (Chen et al., 2015; Li et al., 2016), global climate modeling (Zhou et al., 2015), and aerosol effects on the Asian monsoon (Tsai et al., 2016).

Many workshops have been organized to discuss the progress of this research, and special issues of journals have been published to document the accomplishments of the collaboration. For example, recent meetings include the 10th EACE workshop, entitled "Modeling Aerosols, Monsoon and Climate: Collaborative Research", held 13–14 April 2015 at the IAP, Beijing; and the 13th EAC workshop, entitled "East Asian Climate under Global Warming: Understanding and Projection", held 24–25 March 2016 at Beijing Normal University. In terms of journal publications, Jianping LI (EAC co-coordinator) is currently serving as a Guest Editor for a special issue of *Climate Dynamics*, to document some of the program's research findings.

3. Modeling aerosol–cloud–climate interactions

Several modeling studies have been conducted to investigate specific issues relevant to aerosol climate effects over East Asia. Because of the importance of aerosols to cloud microphysics, we begin by describing the cloud scheme used, followed by the responses of the vertical distribution of cloud properties. The issue of synoptic-scale aerosol variation is then raised within the context of the use of monthly-mean aerosol loadings in current model simulations.

3.1. *NTU cloud scheme*

One of the unique achievements in this collaborative effort has been the incorporation of the NTU cloud scheme in regional models for the purpose of studying aerosol–cloud microphysical interactions. The cloud scheme was originally a two-moment warm cloud microphysical scheme coupled in the Meso-scale Model, version 5 (Cheng et al., 2007). It has three novel aspects. First, this scheme, which was documented in detail in Chen and Liu (2004), was based on statistical analysis of simulation results of a bin microphysical model, so it did not have to assume any specific size distribution for cloud and rain droplets as other schemes. Second, it included a simple aerosol module, which explicitly calculates aerosol processes such as transport, nucleation, resuspension, and wet sedimentation by tracking aerosol mass in hydrometeors. This enables the scheme to simulate the two-way aerosol–cloud interactions to some degree. Third, it employed an embedded parcel method in calculating supersaturation at all levels to better simulate cloud droplet activation (Cheng et al., 2007).

This scheme was further enhanced by importing the mixed-phase cloud parameterization of Reisner et al. (1998)

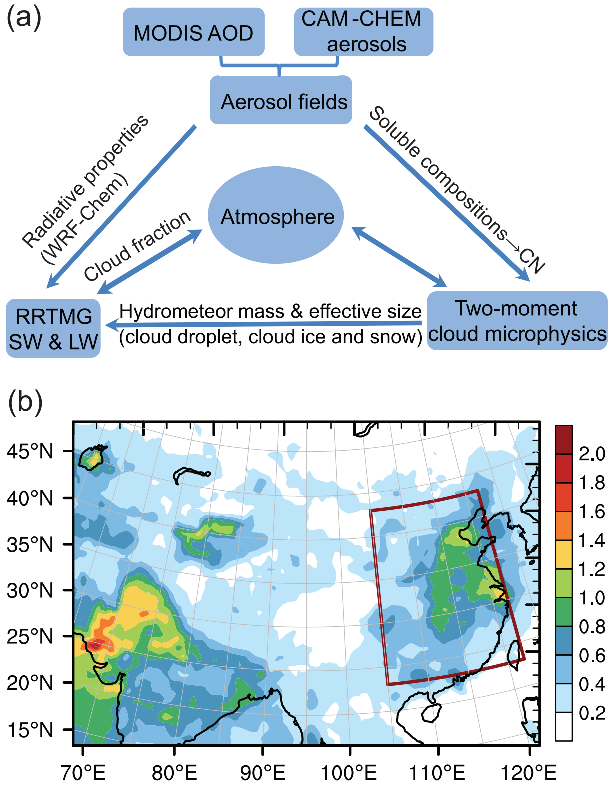
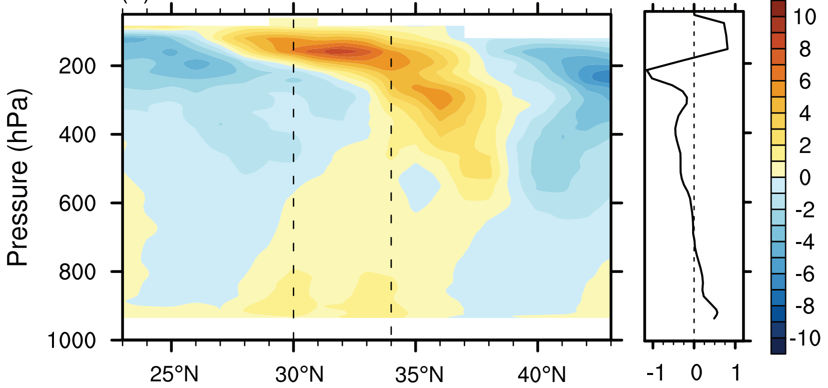


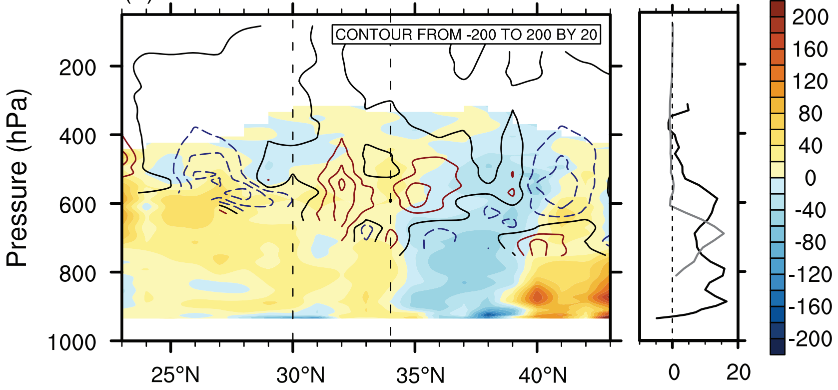
Fig. 3. (a) WRF model configuration used in simulating the changes in vertical distributions of cloud properties due to changes in atmospheric aerosol loadings over monsoon Asia in summer 2008, shown in Fig. 4. Besides modulating hydrometeor mass and size, aerosols also affect cloud fraction through suppressing precipitation, invigorating convection and changing atmospheric circulation and stability. The three-dimensional multi-component aerosol fields are based on aerosol fields from CAM-CHEM simulations, with the spatial distribution scaled by (b) MODIS aerosol optical depth data. The red box shows the eastern China domain (23°–43°N, 105°–122°E) used in the study.

(see Cheng et al., 2010). This version of the NTU scheme predicts both number and mass mixing ratios for five classes of hydrometeors: cloud droplets, rain droplets, cloud ice, snow and graupel, and has been applied in studies associated with midlatitude frontal systems (Cheng et al., 2010), subtropical stratocumulus cloud (Chen et al., 2015; Chen and Wang, 2016; Li et al., 2016), and tropical cyclones (Hazra et al., 2013). Continued development is ongoing [e.g., the parameterization of shape factors and growth habits of solid hydrometeors (see Tsai, 2014)], and one of the active research tasks is to incorporate the NTU cloud scheme into the NCAR Community Climate Model and the IAP's global

(a) Cloud fraction



(b) Cloud water content



(c) Cloud particle size

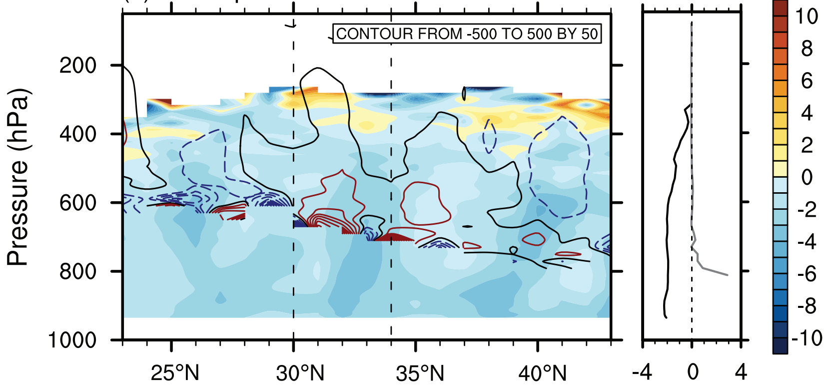


Fig. 4. WRF simulated changes in the vertical distribution of (a) cloud fraction (units: %), (b) cloud water content (units: mg m^{-3}) and (c) cloud particle size (units: μm) along a transect zonally averaged between 105°E and 122°E (red box shown in Fig. 3b), due to the increase in anthropogenic aerosols in summer 2008, with mean profiles in the right-hand part. In the left-hand part of (b, c), color shading represents the liquid water and contour lines the ice water; in the right-hand part of (b, c), black lines represent the liquid water and grey lines the ice water. The dashed lines in the left-hand parts show the boundaries between South China, the Yangtze–Huaihe river valley and North China.

model (Zhou et al., 2015) to study aerosol climate effects. A workshop was held at NTU on 9–10 April 2016 to discuss the latest progress on the use of the NTU cloud scheme in regional and global climate models.

3.2. *Vertical distribution of cloud properties*

In addition to changes in cloud water and droplet size caused by aerosol changes, the cloud fraction may also change due to changes in moisture and circulation associated with aerosol–cloud microphysics–radiation interactions (see Fig. 1). Furthermore, the cloud vertical distribution plays an important role in cloud–radiation interaction and surface temperature: low clouds with more liquid water (and therefore larger optical thickness) reflect more solar radiation, resulting in a surface cooling effect; whereas high, optically thin clouds trap outgoing longwave radiation more efficiently, causing a warming effect.

The WRF model with the NTU cloud scheme has been used to address the responses of cloud vertical properties (fraction and microphysics) to changes in atmospheric aerosol loadings over eastern China. The model configuration is shown in Fig. 3, in which three-dimensional aerosol fields are taken from NCAR/CAM-CHEM simulations (Lamarque et al., 2012) and scaled by MODIS aerosol optical depth (AOD). Changes in vertical distributions of cloud properties were evaluated by comparing two cases in summer 2008: a control case imposing the observed AOD and a sensitivity case having anthropogenic components of the control case reduced by 75%.

As shown in Fig. 4, for the domain average of eastern China, increases in anthropogenic aerosols, as expected, lead to more but smaller cloud droplets and larger cloud water content; the cloud fraction shows an increase at high and low levels, but a decrease at the middle levels. Within this domain, although the cloud droplet size decreases, consistent with increases in aerosol loadings, changes in cloud fraction and water content show strong regional characteristics. Low- and high-level cloud fractions decrease in North China and South China, but increase in the Yangtze–Huaihe river valley (YHRV); the cloud liquid water content increases in South China and the YHRV, but decreases in North China, except north of 40°N. Changes in shortwave and longwave cloud radiative forcing (CRF) at the top of the atmosphere are shown in Fig. 5. The results reveal that the former are dominated by changes in low-level cloud fraction, while the latter are related to changes in high-level cloud fraction. Although

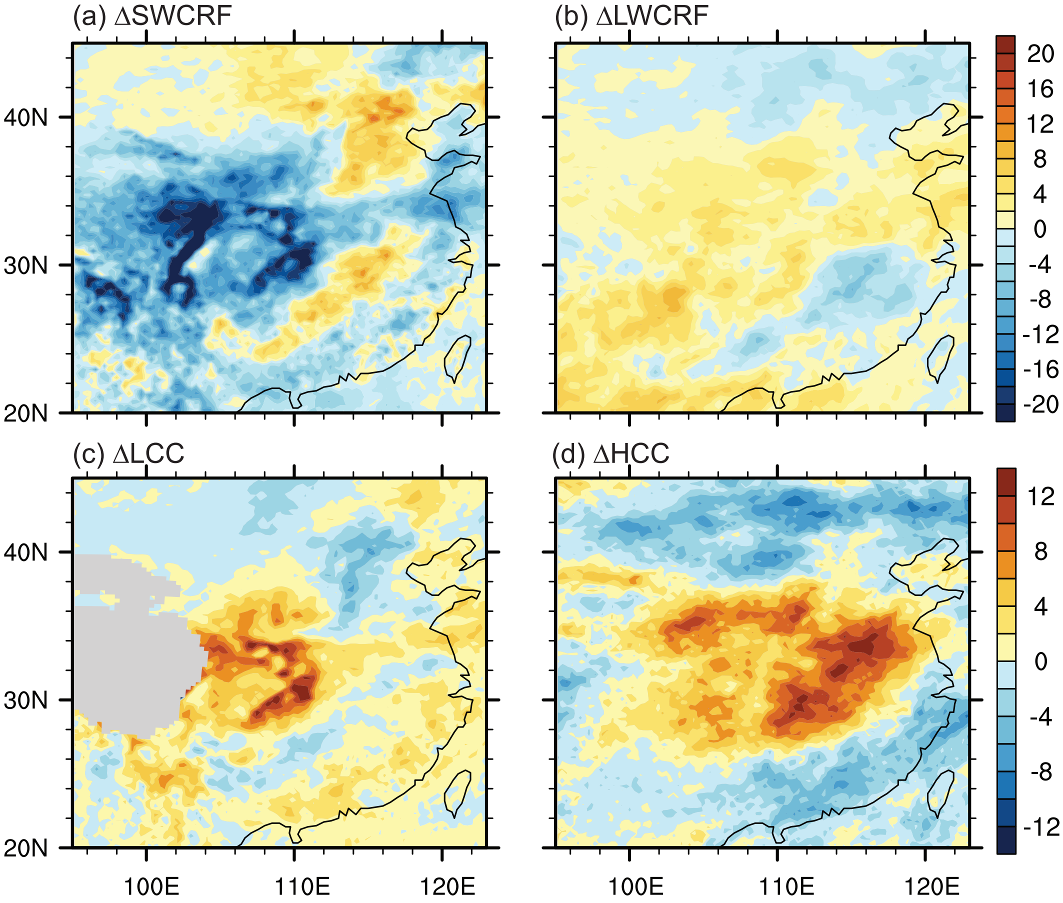


Fig. 5. WRF simulated changes in (a) shortwave and (b) longwave cloud radiative forcing (SWCRF and LWCRF, respectively; units: W m^{-2}) at the top of the atmosphere, and (c) low- (>680 hPa) and (d) high-level (<440 hPa) cloud cover (LCC and HCC, respectively; units: %) due to the increase in anthropogenic aerosols in summer 2008.

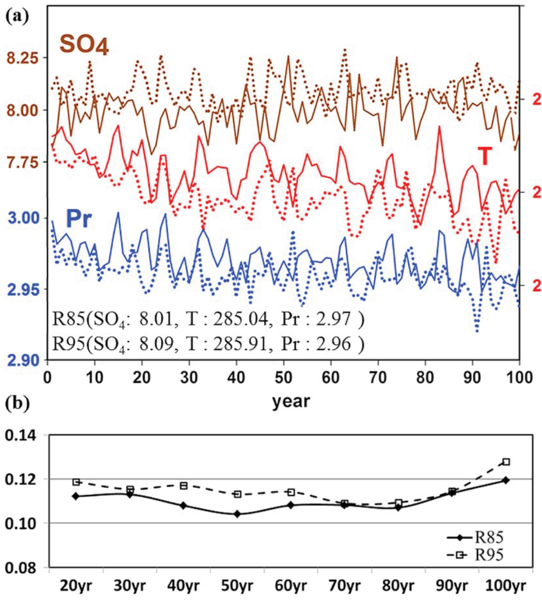


Fig. 6. (a) Global annual mean surface air temperature (T; red; units: K), precipitation (Pr; blue; units: mm d^{-1}) and sulfate aerosol loadings (SO_4; brown; units: mg m^{-2}), for two 100-year CESM simulations, R85 (solid line) and R95 (dash line), with prescribed annual cycles of anthropogenic aerosol emissions in 1985 and 1995, respectively. The means of years 51–100 of the respective parameters are detailed in the figure. Since the yearly surface SO_2 emissions are constant throughout the 100-year run, the sulfate variability is caused by the variability in aerosol–meteorology coupling. (b) Standard deviation of surface temperature calculated based on different data lengths, where "20yr" refers to the data during years 81–100, "60yr" during years 41–100, and so on. [Reprinted from Tsai et al. (2016)]

associations between the aerosol loading and warm cloud microphysical properties, and between cloud properties and CRF, can be clearly illustrated, the physical processes relating aerosol loading and cloud fraction, cloud liquid water content, and ice-cloud microphysics, are less clear. Further analyses are needed.

3.3. *Synoptic-scale aerosol variation*

The "aerosol–meteorology coupling" indicated in Fig. 1 concerns the temporal and spatial distributions of aerosol mass, size and compositions that are strongly coupled with variations of moisture, temperature, winds, and cloud properties (e.g., fraction). The need to address the effects of this coupling in modeling aerosol–cloud–climate interactions was clearly illustrated in Tsai et al. (2016), in which 100-year CESM (global, coupled atmosphere–ocean GCM) simulations with prescribed annual anthropogenic aerosol emissions were conducted. Figure 6, taken from that study, shows that, although the annual SO_2 surface emissions remain unchanged in the individual year of the simulations, the sulfate loading, and surface temperature and precipitation, show interannual variations due to aerosol–meteorology couplings, and certainly decadal variations, in which atmosphere–ocean interactions also come into play. The interannual variations of these parameters are found to be even larger over East Asia. Moreover, even when the aerosol loading is held constant, the synoptic-scale variability of meteorology can still induce significant variations in aerosol climate effects. For example, in the WRF control simulation described in section 3.2, over the Beijing–Tianjin–Hebei region, the means and standard deviations of the AOD values are quite large (Fig. 7), even though the aerosol loading does not change through-

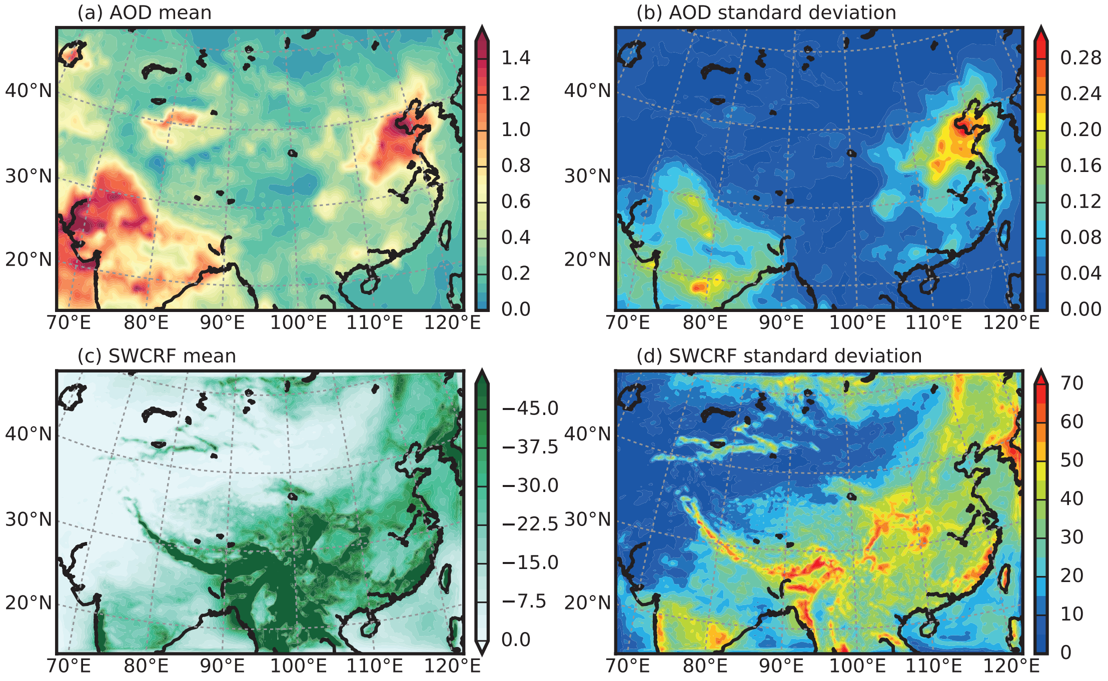


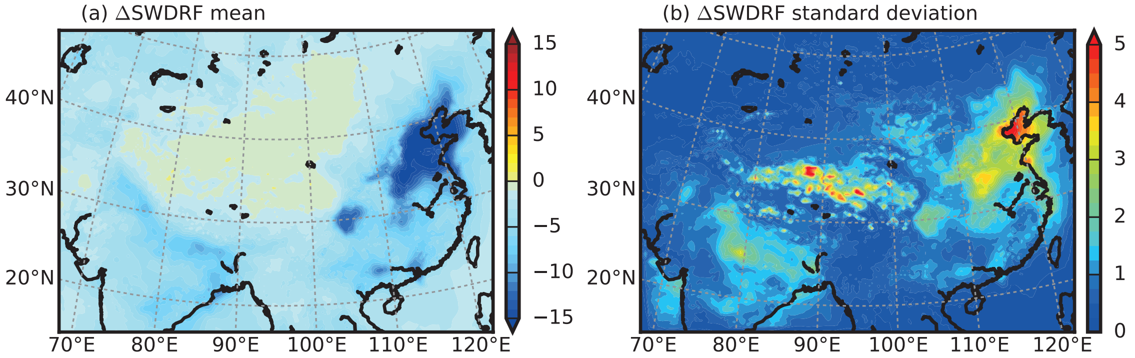
Fig. 7. WRF simulated aerosol optical depth (AOD) and shortwave cloud radiative forcing (SWCRF; units: W m^{-2}) at the top of the atmosphere over East Asia in summer 2008: (a, c) mean values; (b, d) standard deviations due to day-to-day meteorological variations.

out the simulation; also, the associated solar CRF and its standard deviation are substantial. The climate forcing of increased anthropogenic aerosols, shown in Fig. 8, also exhibits significant day-to-day variabilities in shortwave direct radiative forcing and CRF. The variations of changes in shortwave CRF can be a few times larger than the mean values, indicating strong couplings between aerosols and the meteorology at synoptic and intraseasonal scales. The implications of these large variances in aerosol climatic effects are certainly worthy of further investigation.

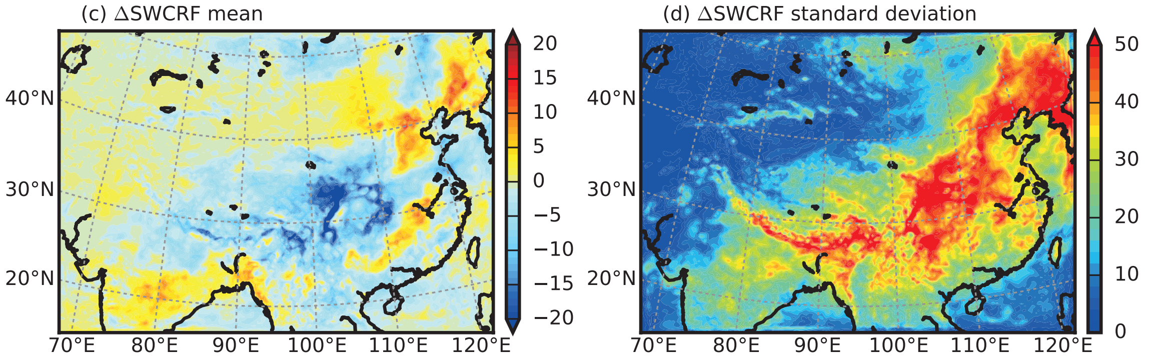
The synoptic-scale variation in aerosols is further illustrated in Fig. 9, showing that the monthly-mean values, which are used in many model simulations, clearly smooth out the day-to-day synoptic variability. We are currently conducting model simulations to examine the sensitivity of the climate effects of aerosols to their synoptic-scale spatiotemporal variations.

4. Closing remarks

The agreement to study the "greenhouse effect" initialized by Professor YE (Koomanoff et al., 1988) has served as an effective platform in the last few decades for close collaborations between Chinese and American scientists. In addition, the initial focus has also evolved into "global changes" covering many topics concerning the Earth climate system as a whole. In this regard, Professor YE's foresight and thoughtfulness have made a significant impact.


(a) ΔSWDRF mean

(b) ΔSWDRF standard deviation


(c) ΔSWCRF mean

(d) ΔSWCRF standard deviation

Fig. 8. WRF simulated shortwave radiative forcing (units: W m^{-2}) caused by increased anthropogenic aerosols at the top of the atmosphere over East Asia in summer 2008: (a, b) direct radiative forcing (SWDRF); (c, d) indirect (cloud) radiative forcing (SWCRF); (a, c) mean values; (b, d) standard deviations due to day-to-day meteorological variations.

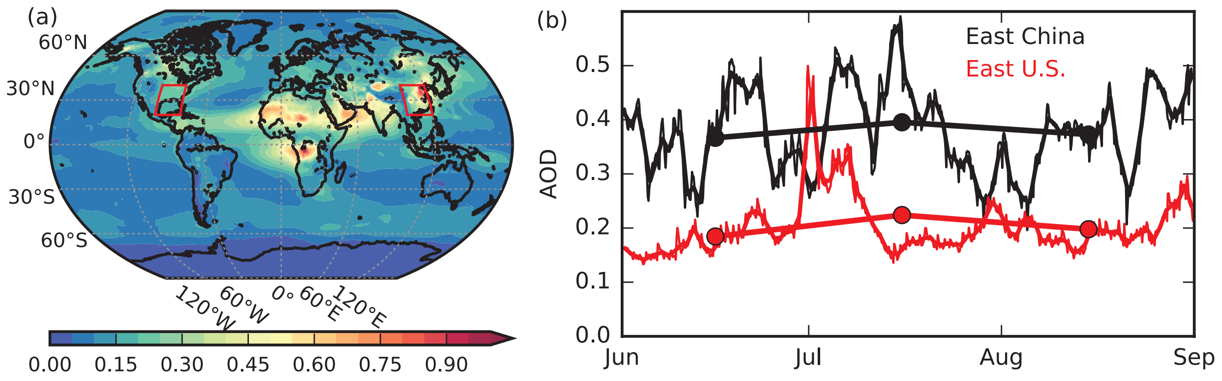


Fig. 9. (a) Aerosol optical depth (AOD) for summer 2015 from the MERRA2 reanalysis. (b) AOD time series of eastern China (black) and USA (red); lines from thin to thick correspond to temporal resolutions of 3-hourly, daily and monthly, respectively.

The close collaborative research on the topic of "modeling aerosol climate effects over monsoon Asia" briefly summarized here will continue. In addition, the development of global and regional models as tools to investigate and understand regional climate changes will also advance further.

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REFERENCES

Chen, G. X., and W.-C. Wang, 2016: Aerosol–stratocumulus–radiation interactions over the southeast Pacific: Implications to the underlying air–sea coupling. *J. Atmos. Sci.*, **73**, 2759–2771, doi: 10.1175/JAS-D-15-0277.1.

Chen, G. X., W.-C. Wang, and J.-P. Chen, 2015: Aerosol–stratocumulus–radiation interactions over the southeast Pacific. *J. Atmos. Sci.*, **72**, 2612–2621, doi: 10.1175/jas-d-14-0319.1.

Chen, J.-P., and S.-T. Liu, 2004: Physically based two-moment bulkwater parametrization for warm-cloud microphysics. *Quart. J. Roy. Meteor. Soc.*, **130**, 51–78, doi: 10.1256/Qj.03.41.

Cheng, C.-T., W.-C. Wang, and J.-P. Chen, 2007: A modelling study of aerosol impacts on cloud microphysics and radiative properties. *Quart. J. Roy. Meteor. Soc.*, **133**, 283–297, doi: 10.1002/Qj.25.

Cheng, C.-T., W.-C. Wang, and J.-P. Chen, 2010: Simulation of the effects of increasing cloud condensation nuclei on mixed-phase clouds and precipitation of a front system. *Atmos Res*, **96**, 461–476, doi: 10.1016/j.atmosres.2010.02.005.

Hazra, A., P. Mukhopadhyay, S. Taraphdar, J.-P. Chen, and W. R. Cotton, 2013: Impact of aerosols on tropical cyclones: An investigation using convection-permitting model simulation. *J. Geophys. Res.*, **118**, 7157–7168, doi: 10.1002/jgrd.50546.

Isaksen, I. S. A., and Coauthors, 2009: Atmospheric composition change: Climate-chemistry interactions. *Atmos. Environ.*, **43**, 5138–5192, doi: 10.1016/j.atmosenv.2009.08.003.

Koomanoff, F. A., M. R. Riches, D. Z. Ye, J. P. Zhao, W.-C. Wang, and S. Y. Tao, 1988: The United States' department of energy and the People's Republic of China's Chinese academy of sciences joint research on the greenhouse effect. *Bull. Amer. Meteor. Soc.*, **69**, 1301–1308.

Lamarque, J.-F., and Coauthors, 2012: CAM-chem: Description and evaluation of interactive atmospheric chemistry in the community earth system model. *Geoscientific Model Development*, **5**, 369–411, doi: 10.5194/gmd-5-369-2012.

Li, J. D., Z. A. Sun, Y. M. Liu, J. N. Li, W.-C. Wang, and G. X. Wu, 2012: A study on sulfate optical properties and direct radiative forcing using LASG-IAP general circulation model. *Adv. Atmos. Sci.*, **29**, 1185–1199, doi: 10.1007/s00376-012-1257-y.

Li, J. D., W.-C. Wang, Z. A. Sun, G. X. Wu, H. Liao, and Y. M. Liu, 2014: Decadal variation of East Asian radiative forcing due to anthropogenic aerosols during 1850–2100, and the role of atmospheric moisture. *Climate Research*, **61**, 241–257, doi: 10.3354/cr01236.

Li, J. D., W.-C. Wang, H. Liao, and W. Y. Chang, 2015: Past and future direct radiative forcing of nitrate aerosol in East Asia. *Theor. Appl. Climatol.*, **121**, 445–458, doi: 10.1007/s00704-014-1249-1.

Li, J. D., W.-C. Wang, X. Q. Dong, and J. Y. Mao, 2017: Cloud-radiation-precipitation associations over the Asian monsoon region: An observational analysis. *Climate Dyn.*, doi: 10.1007/s00382-016-3509-5.

Li, Y. Y., R. C. Yu, Y. P. Xu, and X. H. Zhang, 2004: Spatial distribution and seasonal variation of cloud over China based on ISCCP Data and surface observations. *J. Meteor. Soc. Japan*, **82**, 761–773, doi: 10.2151/jmsj.2004.761.

Li, Z., H. W. Xue, J.-P. Chen, and W.-C. Wang, 2016: Meteorological and aerosol effects on marine stratocumulus. *J. Atmos. Sci.*, **73**, 807–820, doi: 10.1175/JAS-D-15-0101.1.

Reisner, J., R. M. Rasmussen, and R. T. Bruintjes, 1998: Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. *Quart. J. Roy. Meteor. Soc.*, **124**, 1071–1107, doi: 10.1002/qj.49712454804.

Riches, M. R., J. P. Zhao, W.-C. Wang, and S. Y. Tao, 1992: The U.S. department of Energy and the People's Republic of China' academy of sciences joint research on the greenhouse effect: 1985–1991 research progress. *Bull. Amer. Meteor. Soc.*, **73**, 585–594.

Stevens, B., and G. Feingold, 2009: Untangling aerosol effects on clouds and precipitation in a buffered system. *Nature*, **461**, 607–613, doi: 10.1038/nature08281.

Suzuki, K., G. L. Stephens, and M. D. Lebsock, 2013: Aerosol effect on the warm rain formation process: Satellite observations and modeling. *J. Geophys. Res.*, **118**, 170–184, doi: 10.1002/jgrd.50043.

Tao, S.-Y., M. R. Riches, P.-Q. Chen, and W.-C. Wang, 1999: *Greenhouse Effect and Climate Change*: *Advances of the Joint Research Project on CO_2-induced Climate Change*. Department of Energy, USA and the Chinese Academy of Sciences, PRC (1984-1999). China Ocean Press, 171 pp.

Tao, W.-K., J.-P. Chen, Z. Q. Li, C. Wang, and C. D. Zhang, 2012: Impact of aerosols on convective clouds and precipitation. *Rev. Geophys.*, **50**, RG2001, doi: 10.1029/2011RG000369.

Tsai, I.-C., J.-P. Chen, P.-Y. Lin, W.-C. Wang, and I. S. A. Isaksen, 2010: Sulfur cycle and sulfate radiative forcing simulated from a coupled global climate-chemistry model. *Atmospheric Chemistry and Physics*, **10**, 3693–3709.

Tsai, I.-C., W.-C. Wang, H.-H. Hsu, and W.-L. Lee, 2016: Aerosol effects on summer monsoon over Asia during 1980s and 1990s. *J. Geophys. Res.*, **121**, 11 761–11 776, doi: 10.1002/2016JD025388.

Tsai, T.-C., 2014: A multi-moment bulkwater ice microphysics scheme with consideration of the adaptive growth habit and apparent density for pristine ice in the WRF model. PhD dissertation, NTU, 168 pp.

Wang, K. C., R. E. Dickinson, and S. L. Liang, 2009: Clear sky visibility has decreased over land globally from 1973 to 2007. *Science*, **323**, 1468–1470.

Wang, W.-C., W. Gong, W.-S. Kau, C.-T. Chen, H.-H. Hsu, and C.-H. Tu, 2004: Characteristics of cloud radiation forcing over East China. *J. Climate*, **17**, 845–853.

Wang, W.-C., J.-P. Chen, I. S. A. Isaksen, I.-C. Tsai, K. Noone, and K. McGuffie, 2012: Climate-chemistry interaction: Future tropospheric ozone and aerosols. *The Future of the World's Climate*, A. Henderson-Sellers and K. McGuffie, Eds., 2nd ed., Elsevier, 367–399.

Wild, M., 2009: Global dimming and brightening: A review. *J. Geophys. Res.*, **114**, D00D16, doi: 10.1029/2008JD011470.

Zhang, L., H. Liao, and J. P. Li, 2010: Impacts of Asian summer monsoon on seasonal and interannual variations of aerosols over eastern China. *J. Geophys. Res.*, **115**, D00K05, doi: 10.1029/2009JD012299.

Zhang, X. Y., Y. Q. Wang, T. Niu, X. C. Zhang, S. L. Gong, Y. M. Zhang, and J. Y. Sun, 2012: Atmospheric aerosol compositions in China: Spatial/temporal variability, chemical signature, regional haze distribution and comparisons with global aerosols. *Atmospheric Chemistry and Physics*, **12**, 779–799, doi: 10.5194/acp-12-779-2012.

Zhou, L. J., and Coauthors, 2015: Global energy and water balance: Characteristics from finite-volume atmospheric model of the IAP/LASG (FAMIL1). *Journal of Advances in Modeling Earth Systems*, **7**, 1–20, doi: 10.1002/2014MS000349.

Zhu, J. L., H. Liao, and J. P. Li, 2012: Increases in aerosol concentrations over eastern China due to the decadal-scale weakening of the East Asian summer monsoon. *Geophys. Res. Lett.*, **39**, L09809, doi: 10.1029/2012GL051428.